

Current-induced domain-wall motion in synthetic antiferromagnets

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Abstract

Domain-wall magnetoresistance and low-frequency noise have been studied in epitaxial antiferromagnetically-coupled [Fe/Cr(001)]₁₀ multilayers and ferromagnetic Co line structures as a function of DC current intensity. In [Fe/Cr(001)]₁₀ multilayers a *transition from excess to suppressed domain-wall induced 1/f noise* above current densities of $j_c \sim 2 \times 10^5 \text{ A/cm}^2$ has been observed. In ferromagnetic Co line structures the domain wall related noise remains qualitatively unchanged up to current densities exceeding 10^6 A/cm^2 . Theoretical estimates of the critical current density for a synthetic Fe/Cr antiferromagnet suggest that this effect may be attributed to current-induced domain-wall motion that occurs via spin transfer torques.

Mutual interaction between electron spin current and ferromagnetic order has given rise to a variety of spintronic effects and devices. Well known examples are the giant magnetoresistance (GMR) effect (with ferromagnetic layer moments acting on electron spin) [1, 2], and spin-torque phenomena [3, 4, 5, 6] where “free” ferromagnetic layer moments are inverted (excited) or domain walls (DWs) are being displaced [7, 8, 9, 10, 11] by a high density spin current flowing through the nanostructure. These phenomena involve rich new physics and have demonstrated enormous potential for applications.

The main problem which faces the spin-torque is a need to decrease the critical currents which induce the effect. Spin transfer in perpendicularly magnetized media, in exchange-biased spin valves, in ferromagnetic semiconductors [12, 13, 14], or using specific periodic current pulses [15], partially overcome this difficulty. A radically different approach to solve the problem proposes to explore DC current-induced torques in antiferromagnetic (AF) materials [16, 17, 18]. Theoretical estimates suggest the possibility to substantially reduce the critical currents and influence the domain structure of antiferromagnetic films already at critical currents above 10^5 A/cm^2 which are about one order of magnitude below the best reported for the ferromagnetic structures.

Creation of DWs in antiferromagnets is not energetically favorable. For synthetic antiferromagnets, such as [Fe/Cr]_n magnetic multilayers (MMLs), the influence of a magnetic field on the DWs is mainly due to the presence of biquadratic coupling allowing effective displacement of the antiferromagnetic domain walls by the external fields [19]. A relatively low DW pinning energy in fully epi-

taxial Fe/Cr MMLs [20] gives rise to appreciable domain wall magnetoresistance (DW-MR) only at temperatures below 100K [21].

Here we investigate the interaction of DC currents with domain walls in epitaxial antiferromagnetically coupled [Fe/Cr]₁₀ multilayers in a wide temperature range below 300 K and with current densities up to $5 \times 10^5 \text{ A/cm}^2$, by using simultaneous measurements of domain wall magnetoresistance and low frequency noise. While the DW-MR remains practically unchanged for the current densities under investigation, a transition from excess DW induced 1/f noise at low current densities to a suppressed noise at current densities j_c exceeding $2 \times 10^5 \text{ A/cm}^2$ is observed. This unexpected observation could be attributed to current-induced domain-wall motion above the critical current density j_c , which coarsens the DWs and reduces the DW-related noise. Current-induced DW noise in ferromagnetic Co line structures is found to remain qualitatively unchanged for densities up to $2 \times 10^6 \text{ A/cm}^2$ indicating a weaker influence of current on DWs.

Two different epitaxial [Fe(001)/Cr(001)]₁₀ multilayers with the same Cr thickness of 13Å (providing the maximum antiferromagnetic coupling) and with different Fe thicknesses of 24Å (MML1) and of 12Å (MML2) were deposited in a molecular beam epitaxy system on MgO(100) substrates held at 50°C. Detailed descriptions of the sample preparation and characterization (XRD, electron transport, etc.) may be found in Refs. [21, 22]. The samples were patterned to a line structure configuration along the easy (001) axis with a length of 500 μm, a width of 10 μm, and a distance between pairs of oppositely situated voltage probes of 400 μm. Experiments

were carried out with the DC current parallel to the external magnetic field and to the magnetically easy (001) axis. Details of the growth and characterization of 21 nm thick, 10 μm wide and 700 μm long polycrystalline Co line structures can be found in Ref. [23]. The setup employed in electron transport and low-frequency noise measurements has been described previously [24, 25].

Fig. 1a shows the low-temperature in-plane magnetoresistance in samples MML1 and MML2 measured up to high magnetic fields to ensure complete parallel alignment of the Fe layers. The high GMR values (60 – 80%) point to the strong antiferromagnetic coupling and confirm a good epitaxy. We have found, however, that the saturation field H_s is much better defined for MML1, indirectly indicating its enhanced crystalline order in comparison with MML2. In agreement with previous observations, both types of multilayers show an appreciable DW magnetoresistance only at temperatures below 100K [20, 21].

Fig. 1b compares the normalized magnetoresistance measured at a temperature of 77K in MML1 and MML2 for the low magnetic field regions when DWs nucleated at $H = H_n$ and annihilated at $H = H_a$ contribute to magnetoresistance. One clearly observes a less defined DW annihilation field for MML2 in comparison to MML1, which correlates with a much broader field region needed to suppress completely the antiferromagnetic state (Figs. 1a,b). This further indicates a higher local structural order in MML1 in comparison to MML2.

We have found that the DW-MR is independent of the applied current densities within an order of magnitude below the maximum current densities applied. Figure 1c demonstrates that even with the maximum current densities used at T=77K ($j = 3.3 \times 10^5 \text{ A/cm}^2$), the current induced self-field or heating are negligible and practically have no influence on the DW magnetoresistance. To finalize discussion of the low-field electron transport we also mention that the DW-MR is found to be practically independent of orientation of the current in respect to the in-plane magnetic field (see Fig.1d). This clearly indicates absence of anisotropic magnetoresistance, as expected to occur in the strongly antiferromagnetically coupled multilayers with reduced magnetization.

The voltage noise power S_V due to magnetization fluctuations was studied in the frequency range between 1 to 25 Hz. The observed $1/f$ noise was described as $S_V(f, H) = \frac{\alpha(H)V^2}{f}$, with α the Hooke factor and V the average voltage between potential contacts [26, 27]. Figs. 2 and 3 present our main findings: clear suppression of the DW related excess low frequency noise (Hooke factor) in MML1 for sufficiently high current densities. Figs. 2 a,b show data obtained at T=77K: when current densities used exceed $2 \times 10^5 \text{ A/cm}^2$, the excess noise observed for low magnetic fields where DWs are created and propagate is transformed into suppressed noise in the field inter-

val $H_n < H < H_a$. Measurements in similar conditions (77K) for MML2 reveal that the Hooke factor reduced by about an order of magnitude and showed no qualitative changes up to current densities of $5 \times 10^5 \text{ A/cm}^2$. This provides further proof for stronger DW pinning due to higher structural disorder in MML2.

Decreasing the temperature down to 10K substantially reduces the excess DW induced noise measured in MML1 with low current densities (Fig.3a). This is in perfect agreement with suppression of the DW related excess imaginary contribution to magnetic susceptibility due to stronger DW pinning at low temperatures [19]. Noise measured at 10K with low current density ($< 10^5 \text{ A/cm}^2$) weakly increases when DWs are formed. However, for current densities exceeding $2 \times 10^5 \text{ A/cm}^2$ a strong reduction of the normalized noise for the field region where DWs are created and propagate is again observed. Figs.3b,c compare the dependence of the Hooke factor on current density for the field regions with ($H_n < H < H_a$) and without (i.e. for $H > H_a$) the presence of DWs. For T=77K one observes a crossover from excess to suppressed DW noise while for T=10K this crossover is shifted to lower current densities. We believe that some reduction of the current-induced suppression of the DW related noise at the highest current densities and low temperatures (Fig.3c) could be due to Joule heating and Oersted field effects estimated to be of about 10K and roughly 5 Oe for densities of $4 \times 10^5 \text{ A/cm}^2$. We finally mention that qualitatively similar current-induced changes in the normalized low frequency noise have been observed when experiments have been carried out with DC current along the easy axis but perpendicular to the external magnetic field.

It was recently observed that the DW induced noise measured through the field region where DWs are formed, propagate and annihilate in quasi-equilibrium conditions, approximately scales with absolute values of the derivative of resistance *vs.* magnetic field, i.e. $\alpha(H) \propto \frac{\partial R}{\partial H}$ [28]. Figure 3a compares the field dependence of $\partial R/\partial H$ and Hooke factor measured at 10K with a current density of $j=2.3 \times 10^5 \text{ A/cm}^2$. Clearly, the Hooke factor and $\partial R/\partial H$ show qualitatively different field dependences close to the region where DWs are formed and propagate. This observation indicates strongly non-equilibrium DW induced noise at high current densities and also is an indirect proof of setting in motion the DWs in Fe/Cr multilayers by current. Interestingly, we have found that the simple relation between $\partial R/\partial H$ and Hooke factor is reasonably well fulfilled for the noise measurements in the ferromagnetic Co line structure in the field region where DWs are nucleated and propagate up to current densities of about $4 \times 10^6 \text{ A/cm}^2$ (Fig. 4). Qualitatively similar behavior was observed both for 300K and 77K. For current densities exceeding 10^6 A/cm^2 the Oersted field created by the transport current (roughly 12 Oe for the maximum used current density) and Joule heating (being above 10K for

the maximum DC currents employed) may, however, affect both magnetotransport ($\partial R/\partial H$) and low frequency noise in the ferromagnetic Co line structures. This influence is evidenced in the gradual reduction of the domain wall depinning field and related displacement of both maxima in $\partial R/\partial H$ and in Hooke factor above $10^6 A/cm^2$ (see inset to Fig. 4).

We believe our experimental results indicate current-induced motion of the domains in the magnetic microstructure in the Fe/Cr multilayers, as we now explain. First of all, the predominant domain walls are those in the Fe layers induced by local variation of the Cr layer thickness, that causes alternating exchange coupling between the Fe layers [29], as well as extrinsic pinning for the domain walls. Secondly, because the geometry is current-in-plane of the layers we assume that within each layer the same mechanisms prevail that cause current-induced domain-wall motion in ferromagnetic metallic wires. In the presence of extrinsic pinning the critical current for depinning a domain wall is then given by [30, 31] $j_c \sim |e| V_{pin} \lambda / (\hbar \beta A \xi)$, where e is the electron charge, V_{pin} is a typical pinning energy for the domain wall, and A is the cross-sectional area perpendicular to the current direction of a single Fe layer. For our system parameters we find, taking V_{pin}/k_B equal to the temperature below which DW magnetoresistance is observed (~ 100 K), that $j_c \sim \lambda/\beta \xi \times 10^5 A/cm^2$ in terms of the width λ of the domain wall and the typical range ξ of the pinning potential. The critical current is further determined by the dimensionless parameter β that characterizes the degree to which spin is not conserved in the spin transfer process, and/or the degree to which the spin transfer torque is not adiabatic. In our system we expect that λ/ξ is of the order of $0.1 - 0.01$ [29]. Microscopic calculations [32, 33, 34, 35] indicate that β is of the same order as, though generally not precisely equal to, the Gilbert damping constant ($\sim 0.1 - 0.01$) and we conclude that the estimated critical current is in rough agreement with our experimental findings. From this theoretical picture we also conclude that the critical current for moving domain walls is lower in multilayer Fe/Cr than in ferromagnetic wires, mainly because the pinning energy of the domain walls is smaller due to the antiferromagnetic structure. To further corroborate the picture of extrinsic pinning, we remark that estimating the so-called intrinsic critical current for domain-wall motion [30] from the saturation magnetization of one Fe layer ($\sim 2T$) yields a critical current that is several orders of magnitude higher than the current at which the suppression of $1/f$ noise is observed.

Let us finally discuss the possible origin of the unusual minimum in the normalized $1/f$ noise at high current densities and between the DW nucleation and depinning fields. When current-induced torques overcome the DW pinning energy and for high current densities the DWs are set in motion, their continuous displacement could essentially reduce a local variation of the magnetic coupling

sign due to 1 ML steps at the Fe/Cr interface previously reported for Fe/Cr/Fe multilayers [29]. This picture explains the substantial suppression of magnetic $1/f$ noise in the vicinity of the depinning field with current densities $j_c > 2 \times 10^5 A/cm^2$ and is supported by the broad maxima in noise at low temperatures ($T=10$ K) and low currents (Fig. 3c). Indeed, weakly mobile nucleated domains could enhance magnetic frustration and increase the low frequency noise.

In conclusion, detailed studies of domain wall magnetoresistance and noise in antiferromagnetically coupled Fe/Cr multilayers reveal an unexpected dependence of domain wall induced low frequency noise on the current density. This observation could be attributed to current induced domain wall motion. Simple estimates confirm the possibility of a strong reduction of the critical currents needed to move domain walls in synthetic Fe/Cr antiferromagnets in comparison with ferromagnetic line structures.

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- [1] Baibich, N. M. and Broto, J. M. and Fert, A. and Nguyen Van Dau, F. and Petroff, F. and Eitenne, P. and Creuzet, G. and Friederich, A. and Chazelas, J., *Phys. Rev. Lett* **61**, 2472 (1988).
 - [2] Binasch, G. and et al., *Phys. Rev. B* **39**, 4828 (1989).
 - [3] Tsoi, M. and Jansen, A. G. and Bass, J. and Chiang, W.-C. and Seck, M. and Tsoi, V. and Wyder, P., *Phys. Rev. Lett* **80**, 4281 (1998).
 - [4] Myers, E. B. and et al., *Science* **285**, 867 (1999).
 - [5] J. C. Slonczewski, *J. Magn. Magn. Mater* **159**, L1 (1996).
 - [6] L. Berger, *J. Appl. Phys* **81**, 4880 (1997).
 - [7] J. Grollier and P. Boulenc and V. Cros and A. Hamzic and A. Vaurès and A. Fert and G. Faini, *Applied Physics Letters* **83**, 509 (2003).
 - [8] N. Vernier and et al., *EPL (Europhysics Letters)* **65**, 526 (2004).
 - [9] Yamaguchi, A. and Ono, T. and Nasu, S. and Miyake, K. and Mibu, K. and Shinjo, T., *Phys. Rev. Lett.* **92**, 077205 (2004).
 - [10] M. Kläui and C. A. F. Vaz and J. A. C. Bland and W. Wernsdorfer and G. Faini and E. Cambril and L. J. Heyderman and F. Nolting and U. Rüdiger, *Physical Review Letters* **94**, 106601 (2005).
 - [11] D. Ravelosona and et al., *Physical Review Letters* **95**, 117203 (2005).
 - [12] Jiang, Y. and Nozaki, T. and Abe, S. and Ochiai, T. and Hirihata, A. and Tezuka, N. and Inomata, K., *Nature materials* **3**, 363 (2004).
 - [13] Mangin, S. and Ravelosona, D. and Katine, J.A. and Carey, M.J. and Terris, B.D. and Fullerton, E.E., *Nature materials* **5**, 210 (2006).

- [14] Yamanouchi, M. and et al, *Nature* **v. 428**, p. 539 (2004).
- [15] Thomas, L and Hayashi, M and Jiang, X and Moriyai, R and Rettner, C and Parkin, S.S.P., *Nature* **443**, 197 (2006).
- [16] Nuez, A. S. and et al., *Phys. Rev. B* **73**, 214426 (2006).
- [17] Wei, Z. and Sharma, A. and Nunez, A. S. and Haney, P. M. and Duine, R. A. and Bass, J. and MacDonald, A. H. and Tsoi, M., *Phys. Rev. Lett* **98**, 116603 (2007).
- [18] Sergei Urazhdin and Nicholas Anthony, *Phys.Rev.Lett.* **99**, 046602 (2007).
- [19] Aliev, F. G. and Martinez, J. L. and Moshchalkov, V. V. and Bruynseraede, Y. and Levanyuk, A. P. and Villar, R., *Phys. Rev. Lett* **88**, 187201 (2002).
- [20] Aliev, F.G. and Villar, R. and Schad, R. and Martinez, J.L., *Materials Research Society Symposium Proceedings* **v.746**, p.81 (2003).
- [21] Aliev, F.G. and Schad, R. and Volodin, A. and van Haesendonck, C. and Bruynseraede, Y. and Vavra, I. and Dugaev, V.K. and Villar, R., *Europhysics Letters* **63**, p.888 (2003).
- [22] Schad, R. and Belin, P. and Verbanck, G. and Moshchalkov, V. V. and Bruynseraede, Y. and Fischer, H. E. and Lefebvre, S. and Bessiere, M., *Phys. Rev. B* **59**, 1242 (1999).
- [23] Brems, S. and Buntinx, D. and Temst, K. and Van Haesendonck, C. and Radu, F. and Zabel, H., *Phys. Rev. Lett.* **95**, 157202 (2005).
- [24] Guerrero, R. and Aliev, F.G. and Villar, R. and Hauch, J. and Fraune, M. and Gntherodt, G. and Rott, K. and Bruckl, H. and Reiss, G., *Applied Physics Letters* **87**, 042501 (2005).
- [25] Guerrero, R. and et al., *Phys.Rev.Lett.* **97**, 266602 (2006).
- [26] Hardner, H. T. and et al., *Phys. Rev. B* **48**, 16156 (1993).
- [27] Sh. Kogan, *Electronic noise and fluctuations in solids* (Cambridge University press, 1996).
- [28] Jiang, L. and Nowak, E. R. and Scott, P. E. and Johnson, J. and Slaughter, J.M. and Sun, J.J. and Dave, R.W., *Phys. Rev. B* **69**, 054407 (2004).
- [29] Schmidt, C. M. and et al., *Phys. Rev. B* **60**, 4158 (1999).
- [30] Tatara, G. and Kohno, H., *Phys Rev. Lett.* **v.92**, 086601 (2004).
- [31] Tatara, G. and Kohno, H. and Shibata, J., *J. Phys. Soc. Jpn.* **77**, 031003 (2008).
- [32] Tserkovnyak, Y. and et al., *Phys. Rev. B* **74**, 144405 (2006).
- [33] Kohno, H. and Tatara, G. and Shibata, J., *J. Phys. Soc. Japan* **75**, 113706 (2006).
- [34] Duine, R. A. and Nunez, A. S. and Jairo Sinova and MacDonald, A. H., *Phys. Rev. B* **75**, 214420 (2007).
- [35] Piechon, F. and Thiaville, A., *Phys. Rev. B* **75**, 174414 (2007).

FIGURE CAPTIONS

Fig 1. (a) Comparison of giant magnetoresistance $GMR=[R(H) - R(60 \text{ kOe})]/R(60 \text{ kOe}) \times 100$ measured at 10K for MML1 and MML2. The arrows indicate the corresponding saturation fields H_s . (b) Normalized to

zero field ($DW - MR(0) = [R(H) - R(0 \text{ Oe})]/R(0 \text{ Oe})$) value magnetoresistance measured for MML1 and MML2 at 77K. (c) Domain wall magnetoresistance $DW-MR=[R(H) - R(400 \text{ Oe})]/R(400 \text{ Oe}) \times 100$ for MML1 and MML2 measured at $T = 77K$ with different current densities used for the noise measurements. The arrows indicate the DW nucleation (H_n) and annihilation (H_a) fields. (d) Low field magnetoresistance measured at $T = 77K$ with zero bias for MML1 with current either parallel or perpendicular to the external magnetic field.

Fig 2.(a) Dependence of the Hooke factor α on the magnetic field measured for MML1 at 77K with different applied current densities. (b) Hooke factor vs. magnetic field for MML1 at 77K with two different applied current densities shown in logarithmic scale. The normalized noise vs. field measurements obtained with a current density of $j = 3.3 \times 10^5 A/cm^2$ are shown both for increasing and decreasing magnetic field. The experiments have been carried out with DC current parallel to the external magnetic field and to the magnetic easy (001) axis.

Fig 3 (a) Dependence of the Hooke factor α (in logarithmic scale) on the magnetic field for MML1 measured at $T=10K$ with two different applied current densities. For comparison, solid line shows absolute values of derivative $\partial R/\partial H$ measured with current density of $2.3 \times 10^5 A/cm^2$. The vertical arrows mark the regions of nucleation and annihilation of the domain walls determined from low-field magnetoresistance. (b,c) Dependence of the Hooke factor in the current density measured in MML1 with and without domain walls for two different magnetic fields at temperatures of 77K (part b) and of 10K (part c).

Fig 4 Hooke factor α vs. magnetic field measured in the ferromagnetic Co line structure at 77K with current density of $j = 3.3 \times 10^5 A/cm^2$. The insert shows the field values of the maximum in Hooke and related maxima of the derivative $\partial R/\partial H$ (as indicated by dashed circle) as a function of current density.

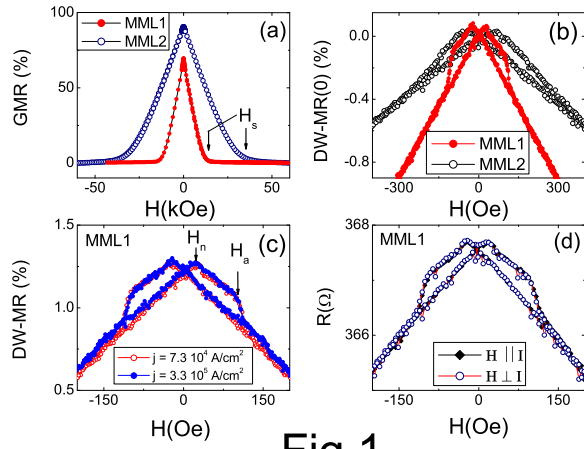


Fig.1

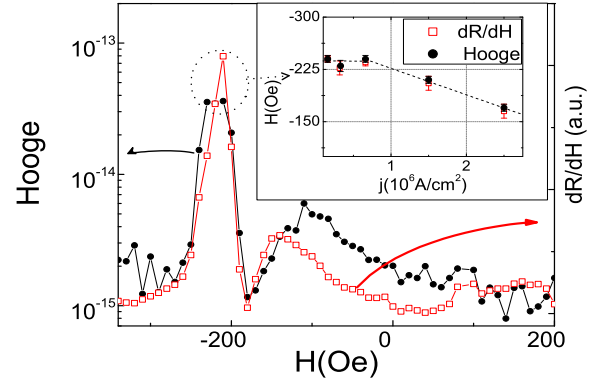


Fig. 4

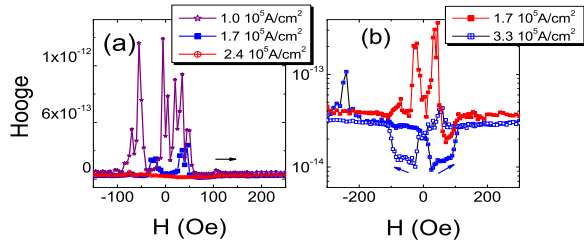


Fig.2

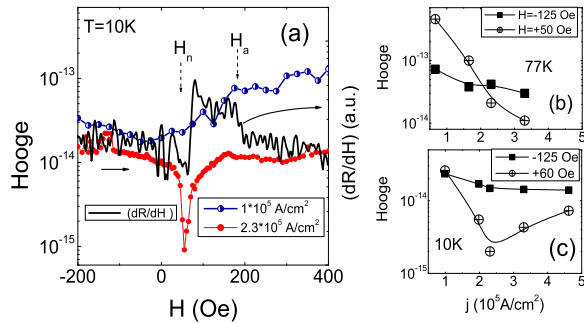


Fig.3